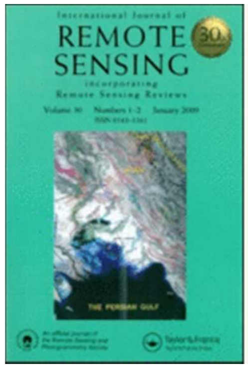

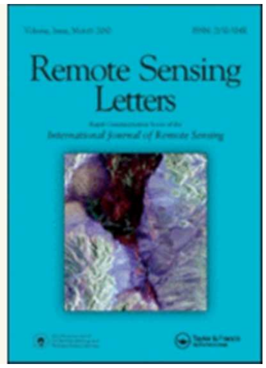

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Global and Regional Drought Dynamics in the Climate Warming Era

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Abstract. According to the 2007 IPCC report, the average global temperature over the past 100 years increased 0.74ºC. The period after 2000 was the warmest, including the two warmest (global land and ocean) years (2007 and 2010) since the 1880s. A warmer world is expected to have tendencies to higher temperature variability increasing the risk of summer droughts, which are supposed to affect a larger area, be longer, more intensive and produce more devastating impacts on the environment and economy. This paper investigates whether such tendencies (global, hemispheric and regional) in drought area, frequency, intensity, duration have already appeared in the warmest decade of the past 100 years. New satellite-based vegetation health (VH) technology and regional *in situ* data were used for this analysis. The VH were used to investigate trends in global and regional drought area for several drought intensities (starting from moderate to exceptional) during the warmest decade, after 2000. Two the most recent strongest droughts, 2010 in Russia and 2011 in the USA are also discussed. During 2001-2012, droughts of moderate-to- exceptional (ME), severe-to-exceptional (SE) and extreme-to-exceptional (EE) severity covered 17-35, 7-15 and 2-6% of the world area, respectively. No trends in drought areas for these levels of severity were found. Regional analysis was performed on Ukraine (from both satellite and *in situ* data). Annual mean temperature of the entire country follows global warming tendency, although the intensity is twice stronger, 1.45°C over 50-year period. The droughts of SE and exceptional severity during the growing season normally affect 25-60 (up to 80% of the major crop area) and 5-10% (up to 20) of the entire country and the latest is leading to up to 40% of losses in Ukrainian grain production.

1. Introduction

The recent IPCC report stated that the average Earth surface temperature in the past 100 years increased 0.74° (Solomon et al, 2007). A warmer world is expected to have much higher temperature variability, which will increase the risk of summer droughts, especially in the mid- and low- latitudes of continental interior. Drought prognosis for the end of this century due to global warming are bleak since a proportion of the land surface with extreme droughts is likely to increase. Moreover, the number of extreme droughts per 100 years and their duration are likely to increase by factors of two and six, respectively (Blunden, et al., 2011). Following the rising global temperatures, it is anticipated that some regions (for example southern Europe) will experience shortages of summer precipitation leading to an enhanced evaporative demand and reduction of soil moisture, that would inevitably lead to more frequent and more intensive droughts. The period after 2000 was the warmest including the 2007 and 2010, the two warmest years when unusually strong droughts affected western USA, northwestern China, central Europe and Russia (Levinson and Lawrimore 2008; Blunden et al 2011). Finally, the most recent strong event is the 2011 drought in the southern USA (http://agecoext.tamu.edu/fileadmin/user_upload/Documents/Resources/Publications/RecentDrought.pdf).

Discussing droughts in a future, warmer climate, many publications emphasize potential for a considerable increase in drought area, frequency, intensity, duration and impacts (USGCRP 2012). However, there are no discussions concerning these tendencies during the period of intensive global warming in the past 30 (1980-2010) and especially the last 11 (2001-2011) years. It is quite possible that such tendencies have already started globally and especially regionally, since regional warming in the last few decades in some areas was much more intensive than global (Blunden et al 2011). Therefore, the goals of this paper were to investigate global, hemispheric and regional trends in drought area, frequency, intensity, duration and some impacts. These tendencies will be investigated using new satellite-based vegetation health technology and regional in *situ data.*

2. Drought importance

Drought is important because it has wide-ranging impacts on water resources, ecosystems, agriculture, forestry, energy, human health, recreation, transportation, food supply and demands and other resources and activities. Besides, drought often covers large area over several months, including cases when it is lingering for years. For example, in the recent decade, severe-to-exceptional droughts covered up to 18% of the globe and continued intermittently for a few years in such regions as Australia and Eastern Africa. Compared to other weather-related disasters, drought affects the largest number of people in the world, nearly quarter of million each year. Drought is the most costly disaster: since 2001, drought losses in the 42 highest ranked countries are estimated around $932 billion (http://www.emdat.be/old/Documents/Publications/publication_2004_emdat.pdf (accessed August 26, 2011). In the USA, a country of high technology, drought is estimated as 14 “billion-dollar” annual event in the last 30 years, totaling more than $180 billion in damages and losses (NCDC 2011). In developing countries, the effects of drought are more devastating, leading not only to food shortages but famine, population migration and mortality.

Another specificity of drought compared to other large-scale weather disasters is difficulties in its detection, monitoring and especially prediction because drought is a very complex and least understood phenomenon (Whilhit 1993). Although it is known that drought is a period with dry and hot weather, even a few months with such weather does not necessarily indicate drought, if the preceding to dryness period was quite wet. Since drought is a multi-dimensional phenomenon by its appearance, properties and impacts, weather-based parameters and indices are insufficient to characterize special and temporal drought features, especially such characteristic as drought start, which is important for timely initiation of mitigating measures. Another specific drought feature is its cumulative development with the following cumulative impacts which are not immediately observable. By the time when damages are visible, it is too late to mitigate the consequences. The latest is very important in regions and countries with limited and/or variable water supplies and which economy is highly depended on agriculture.

3. Remote sensing for drought management

The efforts to monitor droughts were traditionally based on climate and hydrological parameters and indices to track changes in weather and hydrological cycle. However, since weather station network is sparse, especially in the developing countries and ecologically marginal areas, satellite technology has been successfully added to drought management in the recent two-three decades (Cracknell 1997). Satellites provide synoptic view, repeat coverage, spectral diversity collected in a consistent, systematic, and objective manner. Satellite data are filling observational gaps between weather stations, which is crucial in monitoring moisture and thermal supplies in many areas of the variable world. Another important feature of satellite data and indices are their ability to provide cumulative assessment of climate and weather impacts on land and atmosphere, which is crucial for drought management since drought is normally developing cumulatively. Over the years, satellite remote sensing has proved perfect utility for operational drought management as a separate tool and also complementing *in situ* (weather) data (Kogan 2002).

In the past two decades, satellite-based drought detection technique was improved and drought monitoring has been successfully implemented using data obtained from the Advanced Very High Resolution Radiometer (AVHRR) on NOAA polar orbiting satellites (Cracknell 1997). This operational information has been provided weekly to NOAA web for every 4 and 16 km of the globe (http://www.star.nesdis.noaa.gov/smcd/emb/vci/VH/index.php). This drought monitoring method will be considerably improved with the new operational satellite technology, which started in October 2011 with the launch of the NPOESS (National Polar-orbiting Operational Satellite System) Preparatory Platform (NPP) with many advanced sensors on board. The new Visible Infrared Imager Radiometer Suite (VIIRS) will provide much higher special (371 m) resolution and four times more spectral bands (compared to its predecessor) to measure radiance. Besides, VIIRS will provide exceptional data quality due to on board calibration of visible channels, narrow response function and consequently, better quality of the Normalized Difference Vegetation Index (NDVI), advanced monitoring of forested area. Moreover, VIIRS data will improve characterization of land surface through the development of new parameters (for example, vegetation indices from mid –IR channels, net primary production, leaf area and others).

4. Vegetation health method for drought monitoring

Vegetation health method is a new tool designed to estimate the entire spectrum of vegetation condition or health from AVHRR-based Vegetation Health (VH) indices. Remote sensing of VH is based on the properties of green vegetation to reflect and emit solar radiation. In drought-free years, green and vigorous vegetation reflects little radiation in the visible (VIS) part of solar spectrum (due to high chlorophyll absorption) and much in the near infrared (NIR) part (due to scattering the light by leaf internal tissues and water content). Following these properties, the difference between NIR and VIS becomes large, indicating that vegetation is very green and vigorous. Drought normally depresses vegetation greenness and vigor (due to a reduction in chlorophyll and water content) and canopy area leading to an increase in the VIS, decrease in the NIR and a reduction in NIR-VIS. This principle is used in construction of the Normalized difference vegetation index [NDVI=(NIR-VIS)/(NIR+VIS)] which became the most widely used for environmental monitoring because it correlates with vegetation biomass, leaf area index and crop yield (Cracknell 1997).

However, it turned out that NDVI alone is not sufficient for monitoring vegetation health and drought. The afternoon temperature of vegetation canopy is an extremely important characteristic for estimation of vegetation condition. Therefore, land cover thermal characteristic was added to the NDVI tool. In addition, both NDVI and thermal parameter were compared to their climatology calculated from the 32-year AVHRR data. Following these principles, three indices were developed; Vegetation condition (VCI) from NDVI, Temperature condition (TCI) from 10.3-11.3 µm infrared channel's measurements of brightness temperature (BT) of land surface and vegetation health index (VTI) from the combination of VCI and TCI for estimation of total health (Kogan 1997, , Kogan et al 2012). The NDVI and BT were well calibrated and low/high frequency noise was removed from the data. The VCI, TCI and VHI were validated (pre- and post launch) to be an appropriate indicators of moisture, thermal and total vegetation health conditions, respectively. The indices values change from zero, indicating extreme stress to 100, indicating very favorable conditions; close to normal conditions are approximated by the values around 50. VH-designed drought monitoring is based on the numerical analysis of vegetation stress from a lower greenness and above normal temperature; these conditions indicate moisture and/or thermal vegetation stress. In dry years, high temperatures at the background of insufficient water supply trigger an overheating of the canopy, which intensifies the impact of moisture shortage on vegetation. Drought warning is issued if VH values decrease below 40. The details of the algorithm are presented in Kogan (1997).

5. Unusual droughts in 2010-2011

In order to demonstrate the utility of VH method in early drought detection and monitoring, the most recent 2010 and 2011 droughts are discussed here since they had huge economic consequences. The 2011 US drought covered southern states and was centered on Texas, Oklahoma and New Mexico, which experienced primary drought hit. Summer in these states was the hottest on record and it is estimated that the Texas drought only will cost more than $5.2 billion in agricultural losses (AgriLife 2011). Additional losses came from wildfires, depletion of water in lakes and reservoirs, tourism, and deterioration of human health and ways of living. Figure 1 shows Vegetation health index (VHI) in mid-July 2011. The red area indicates the epicenter of the 2011 drought where vegetation deteriorated enormously (VHI<15). Analysis showed that thermal conditions (TCI) played major role in depletion of soil moisture and drought development. Thermal stress started as early as in February 2011 when soil moisture conditions have been adequate, intensified strongly in March-April and continued to be strong through the entire season. Overall, based on both moisture and thermal stress, exceptional (the strongest) drought (occurs every 9-20 years) plagued 8 percent of the contiguous United States and extreme-to-exceptional drought covered nearly 15 percent of the country in 2011 (Fig 2). State level drought of exceptional intensity affected nearly 40% of Texas and Oklahoma (30% New Mexico) and severe-to-exceptional intensity hit 60% of Texas and 70% of Oklahoma (Fig 2); droughts of any intensity covered the entire states. Before 2011, large-scale and intensive US droughts affected western USA (especially Colorado) in 2002 and Great Plains in 1988.

The 2010 drought in Russia was very long, intensive, occupied a huge area and caused serious damages to the environment, economy and human health. Based on VHI, this drought started in May and continued through November. A very specific drought feature, similar to the USA, was intensive thermal stress (Fig 3), which started in April covering the entire European Russia and western part of Russian Asia. An excessive heat dried up quickly soil moisture deteriorating vegetation health. As the result of the 2010 drought, Russian grain production dropped considerably. The drought, which continued through November affected (due to low soil moisture) also the 2011 harvest. Following this drought and grain embargo imposed by the Russian Government, global wheat prices increased sharply since Russia is one of the main exporters of grain to the world market (Kramer 2010). Drought has also triggered hundreds of fires accompanied by a very heavy and long-lasting smoke and heat waves, which affected human health and enhanced considerably death rate in Russia.

6. Drought trends in the warmest decade

As it has been indicated, the period after 2000 was the warmest in the past 100 years. A few unusual drought events have already occurred during this period. They were characterized by an extreme severity, high frequency, huge affected area, long duration and enormous impacts on economy, environment and human lives. These exact drought features have already been emphasized by the recent IPCC report and a number of research as some of the drought consequences of the warmer climate (Solomon et al, 2007, USGCRP 2012). It is quite possible that such tendencies have already begun, since the global temperature increased 0.74° (including 0.3° in the past 30 years). Therefore, this section investigates drought tendencies in VH time series.

Figure 4 shows global and regional dynamics in drought area for different levels of drought severity during the warmest decade of the current millennium. Drought events were identified for each pixel following VH criteria (below 40) and percent drought area was calculated relative to the total number of pixels in the investigated area. Following the “US Drought Monitor” criteria (http://droughtmonitor.unl.edu/), three levels of drought intensity (ME - from moderate to exceptional, SE – from severe to exceptional and EE – from extreme to exceptional) were investigated. These intensities were selected because the droughts in these categories considerably reduce agricultural production, creating imbalance between grain production and consumption. Global analysis indicate that during the warmest decade 17 to 35% of the world (the deserts were excluded) experienced droughts of ME severity, 7-15% - SE and 2-6% - the most dreadful EE. Another important conclusion is that there is no trend in drought areas for all three levels of severity.

Regional analysis was performed on Ukraine (located in the southeastern Europe) because in addition to satellite data, we also collected 50-year weather and crop data for trend analysis. Ukraine has a large area (604 thousand km²) and is a very important grain producing country, making essential contribution to global grain trade. The country has the most productive chernozem soils favorable for growing grain but crops suffer from droughts every 2-4 years, leading to considerable losses of production (Kogan 1985). VH-based dynamics of drought area for the entire Ukraine and the major grain area, located in the southern and central parts is shown in Fig 4. The droughts stronger than severe (SE) during the growing season normally affect between 25 and 60% of the entire Ukraine and up to 80% of the major crop area; the most dreadful (EE) droughts affect 5-10% of the entire country and up to 20% of the major crop area leading to up to 40% of losses in production. During the indicated 11-year period, droughts of severe and higher intensity occurred almost every other year and affected more than 20% of Ukraine territory. Five droughts (2003, 2007, 2008, 2009 and 2010) covered between 40 and 60% of the country and up to 80% of the major grain crop area. Considerable damage to grain production was done by the three-year drought, which started in 2007, centered on the major crop area and affected the entire growing season.

Finally, Table 1 presents trend analysis in the average for the entire Ukraine (from 180 weather stations) temperature, cumulative precipitations, snow depth and area of winter wheat kill during the 50-year period from 1960 to 2010. It is important to emphasize that the entire Ukraine follows global annual warming tendency, although the intensity is much stronger, 1.45°C over five decades. However, increase in Ukrainian temperature during the warm period was weaker (1.10°C) compared to the cold period (1.35°C) and much weaker (2.5 times) than winter minimum temperature increase (2.80°C). Another important consideration of Ukrainian climate that at the background of intensive temperature increase, precipitation during these 50 years also increased by around 40 mm in both annual and warm periods while decreased 23 mm in the cold season. Most probably because of this combination (temperature and precipitation increase) drought area and intensity did not experience any trends (Fig 4). Another important consideration of climate and agriculture in Ukraine are tendencies in snow depth and minimum winter temperatures because these parameters control the area of winterkill for winter wheat which is the dominant grain crop in Ukraine. In general, a reduction of snow depth increases winterkill area while temperature growth suppose to offset this negative impact. This is what Table 1 is showing: in spite of snow depth reduction (10 cm per 50 years), considerable winter temperature increase led to 10% reduction of winterkill area.

7. Conclusions

Global analysis indicate: (1) during the warmest decade, after 2000, the 17 to 35% of the world experienced droughts from moderate to exceptional intensity, 7-15% - severe to exceptional and 2-6% - the most dreadful exceptional droughts. Two droughts, 2010 in Russia and 2011 in the USA stand out by their intensity, affected area and huge economic consequences. Other two unusual cases of the past 11 years are multi-year droughts in Australia and the Horn of Africa. Regional analysis indicate: (a) similar to the globe, drought area in Ukraine does not experience any trend after 2000, although the las 50-year country average annual temperature increased 1.45°C (twice above the global increase). (b) Winter temperature increase in Ukraine is stronger than summer. (c) Total annual precipitation increased by 40 mm offsetting drought intensification due to a warmer climate. (d) Strong increase in absolute minimum winter temperature is leading to the 10% reduction of winterkill area although declining snow depth slow down this process. (e) The droughts of severe-to-exceptional and exceptional severity during the growing season normally affect 25-60 (up to 80% of the major crop area) and 5-10% (up to 20%) of the entire country and the latest is leading to up to 40% of losses in Ukrainian grain production every 3-5 years. Finally, the new satellite-based Vegetation health method used before for real time monitoring large-scale weather hazards and their impacts on crops and pasture production was successfully applied for climatic aspects of droughts.

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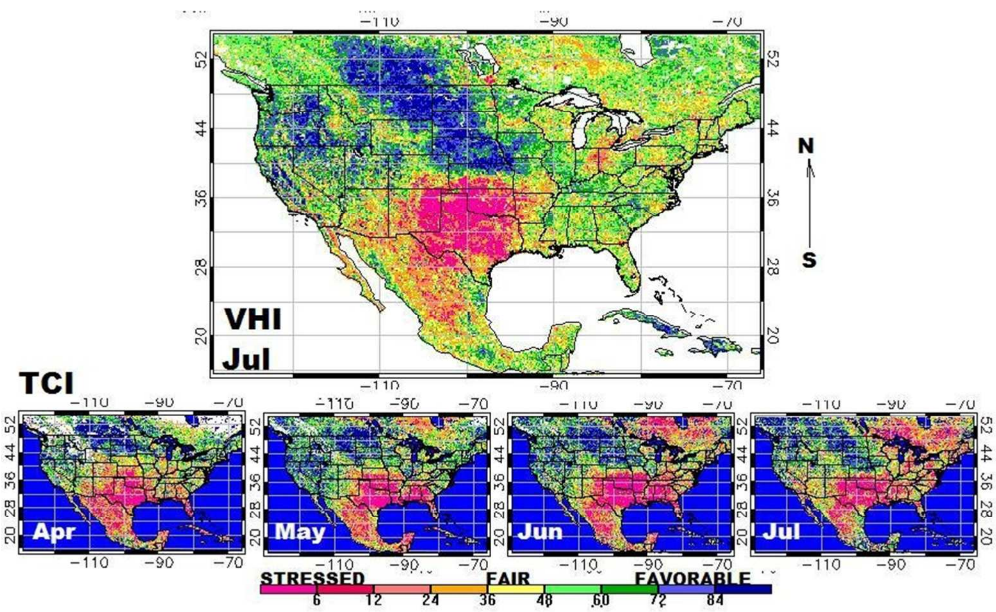
Table 1. Changes in climate and agricultural indicators during 1950-2010, Ukraine

Period	Temperature (°C/Decade)	Precipitation (mm/Decade)	Snow Depth (cm/Decade)	Winter Kill Area (%ofTotalPlanted/ Decade)
Mean Jan-Dec	0.29	8.5		
Mean Jun-Aug	0.22	7.9		
Mean Dec-Feb	0.27	-4.6	- 2.0	-2.0
Minimum Dec-Feb	0.56			

Note: Positive sign means increase, negative - decrease



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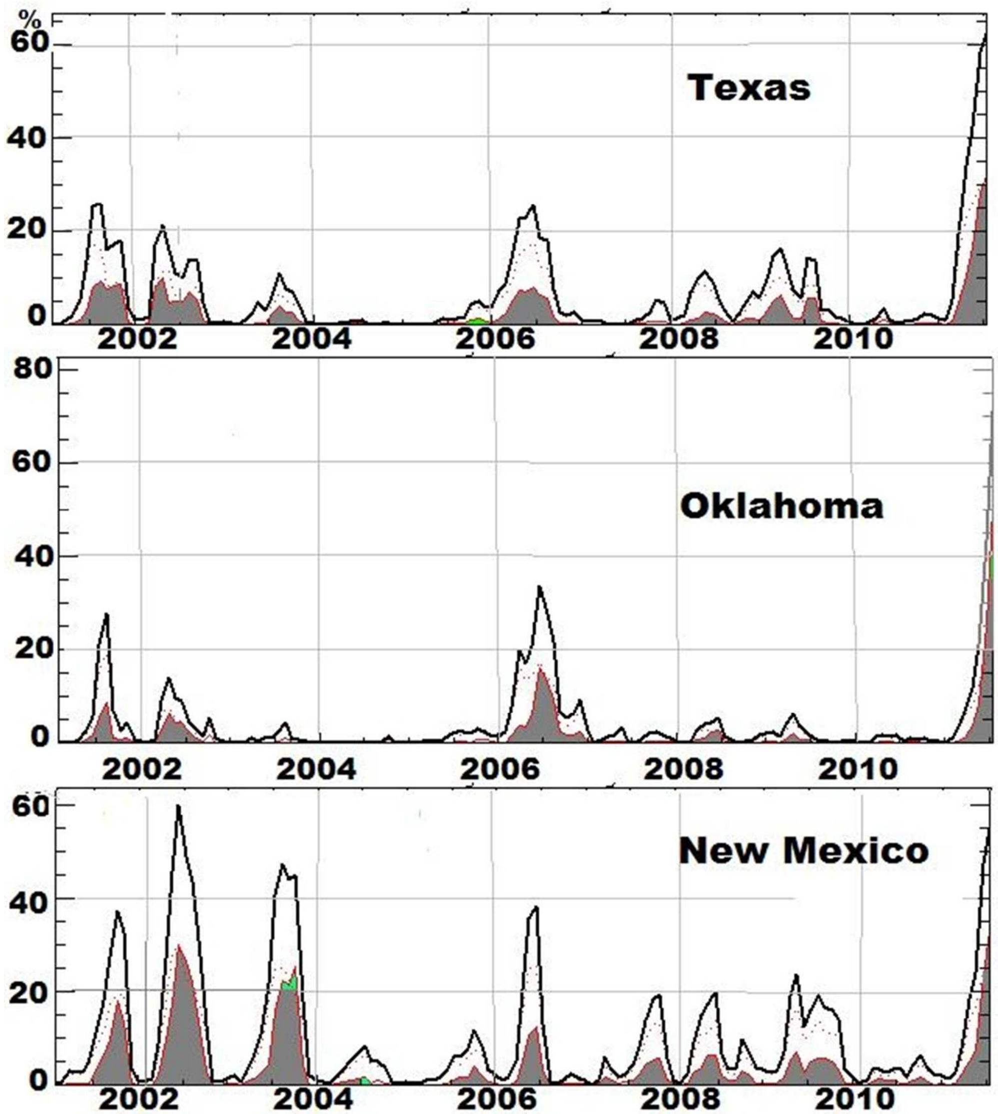

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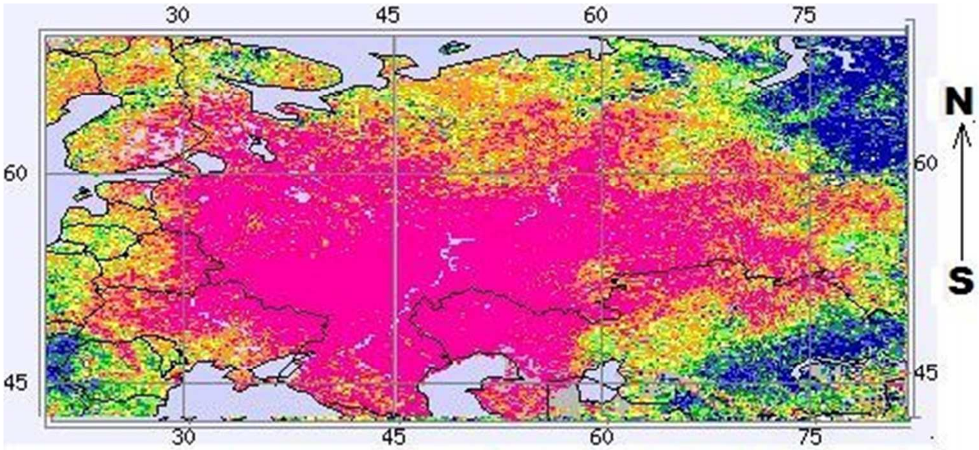

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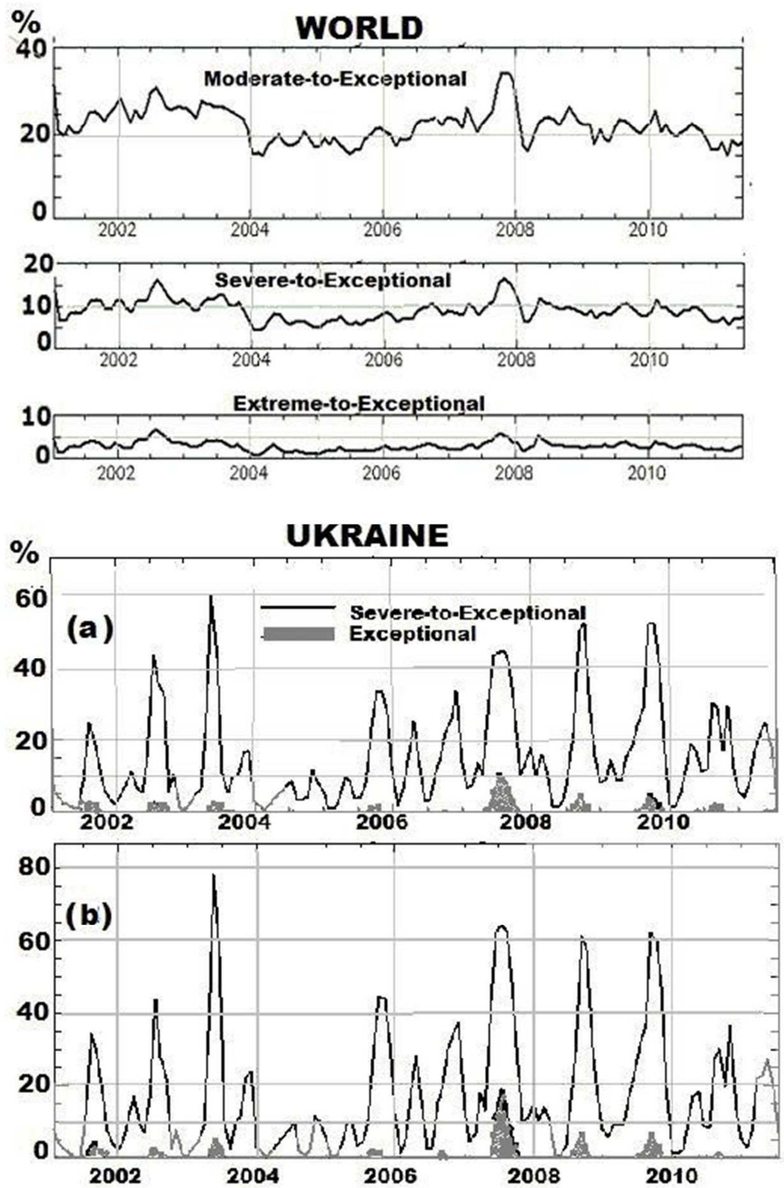

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